DOES IO HAVE A MUSHY MAGMA OCEAN? L. Keszthelyi[1,2], A. S. McEwen[1], G. J. Taylor[2], [1]Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721, [2]Hawaii Institute of Geophysics and Planetology, University of Hawaii at Manoa, 2525 Correa Rd., Honolulu, HI 96822 (lpk@lpl.arizona.edu)

The recent observations suggesting that Io has widespread ultramafic volcanism are not expected in a highly differentiated, solid, Io. A partly crystallized (i.e., mushy) magma ocean provides the simplest alternative explanation.

The idea that Io might have a molten interior was first suggested by Peale et al. in 1979 [1]. Subsequent analysis showed that run-away melting was difficult to achieve and that a completely molten interior was unlikely [2,3,4,5]. Instead, the more detailed modeling of tidal heating suggested that there were two likely states for Io's interior: either (a) mostly solid with only a few pockets of partial melting in the asthenosphere or (b) a crystal-rich fluid mush [5,6,7]. Most recent studies have assumed that Io is largely solid [8,9,10] even though the mushy Io remained plausible [11].

Recent results now make the solid Io less likely and lend support to the mushy magma ocean model. First, if Io were largely solid, the intense volcanism should have produced a strongly differentiated body [10,12]. In the absence of subduction zones, there simply is no efficient way to mix the melts back into the region where they were formed. This differentiation process is expected to produce a ~50 km thick crust composed of a wide range of moderate melting temperature, alkali- and silica-rich, low density rocks. The bulk of the mantle would be of intermediate density and a very refractory, magnesium-rich composition dominated by forsterite. The dense, iron- and calcium-rich rocks would be expected to form a lower mantle [10].

The second key new observation is that very high temperature volcanism is common on Io [13]. Some of these lavas have minimum temperatures above 1500K, hotter than typical terrestrial basalts. While the lavas may be somewhat super-heated if they rapidly rise from deep within the mantle, these lavas must be ultramafic in composition to fit these temperatures. There is also the more tentative identification of magnesium-rich orthopyroxenes in the lavas [13]. Based on the limited data available to date, it seems possible that these ultramafic lavas are not just common, but are ubiquitous.

These very high temperature melts pose a series of difficulties for the differentiated, solid Io model. Such melts would be expected to be generated in the refractory mantle, if it were hot enough. However, these melts would be significantly denser that the overlying crust and could only be erupted if the magma source were ~100km deep. More troubling is the problem of heating the refractory upper mantle hot enough to melt without completely melting the lower melting temperature crust and lower mantle. Finally, the expected composition of the ultramafic lavas would be dominated by olivine. The observed pyroxenes would have to result from crustal contamination during ascent.

If ultramafic melts are ubiquitous, a magma ocean is inevitable. Assuming any reasonable bulk composition for the silicate mantle of Io, melts with temperatures >1500K imply high degrees of partial melting - most likely ~40-60% melting. If the high temperature volcanism is common or ubiquitous, it implies that this high degree of partial melting is common or ubiquitous under Io's lithosphere. A global layer of 40-60% partial melting would constitute a mushy magma ocean.

The resulting model for the interior of Io fits the observations to date and is remarkably self-consistent. First, this high degree of melting at the base of the crust provides a means to mix the volcanic products back into the mantle, allowing Io to remain largely undifferentiated despite the intense volcanism. At 40-60% partial melting the base of the crust would be soft enough to be swept up by the convecting magma ocean, thoroughly mixing the crustal material back into the interior of the body.

Starting with the assumption that the silicate portion of Io remains well-mixed, it is possible to use the MELTS program [14] to investigate the basic petrology of the mushy magma ocean. The bulk composition of Io is thought to be depleted in volatiles, similar to CM chondrites [15] and the core of Io should take up 20% of its mass in the form of a Fe-FeS mixture [9]. The expected melts from a mushy magma ocean of this composition will be rich in magnesian orthopyroxenes.

The percentage of melting varies with pressure inside Io. For the estimated bulk composition, if the magma ocean is 40-60% melt at 100 km depth, it will be 10-30% liquid at the core-mantle boundary. Thus the bottom of the magma ocean will be significantly more viscous than the upper part, but will still be many orders of magnitude weaker than a solid rock. This viscosity distribution would suggest that the majority of the tidal heating will be in the upper part of the magma ocean, but a significant fraction will be dissipated throughout the ocean. This distributed heat should drive convection within the mushy ocean into the "hard" regime, suspending the crystals and keeping it well-mixed. However, the heat distribution near the base of the crust will be more similar to the "thick asthenosphere" models than to a homogeneous dissipation model. This would suggest a concentration of active volcanoes in the equatorial region of Io [6]. While the distribution of volcanic features appears quite uniform [16], there does seem to be a equatorial concentration in active plumes and persistent or long-lived hot spots [17].

The one major anomaly is Loki, which releases ~25% of the observed heat flux from Io. Loki also produces vast amounts of lavas with intermediate temperatures, appropriate for mafic, but not ultramafic lavas [17,18]. We speculate that Loki might be the after effects of a foundered crustal block. The plug of material rising from the magma ocean to fill the hole in the crust would be separated from the main ocean and slowly cool and fractionally crystallize. Intermediate temperature lavas could be produced and exposed quite regularly.

The idea that a magma ocean might currently exist in our solar system is exceedingly exciting. It potentially provides the opportunity to make observations that would constrain the global magma oceans hypothesized to have existed on the Earth and Moon very early in their histories. However the fact that Io's (potential) magma ocean is continually heated by tidal dissipation and has arrested its freezing also suggests that there should be important differences between the Ionian ocean and the terrestrial and lunar ones.

There are several potential future observations that could confirm (or refute) the existence of a magma ocean on Io. Given an assumed initial composition, the bulk density of a solid vs. partially molten Io are significantly different. The improved gravity data from the I24 and I25 orbits of Galileo might have sufficient precision to distinguish these models. Other tests that Galileo may provide include searching for an intrinsic magnetic field, better estimates of lava temperatures and compositions from NIMS, and improved estimates of heat flow as a function of latitude from PPR. A magma ocean will also affect the magnitude of the tides on Io, the orbital librations, and allow non-synchronous rotation and polar wander. Ultimately, the most definitive test will come with the landing of seismometers on Io and observations of the attenuation of shear waves.

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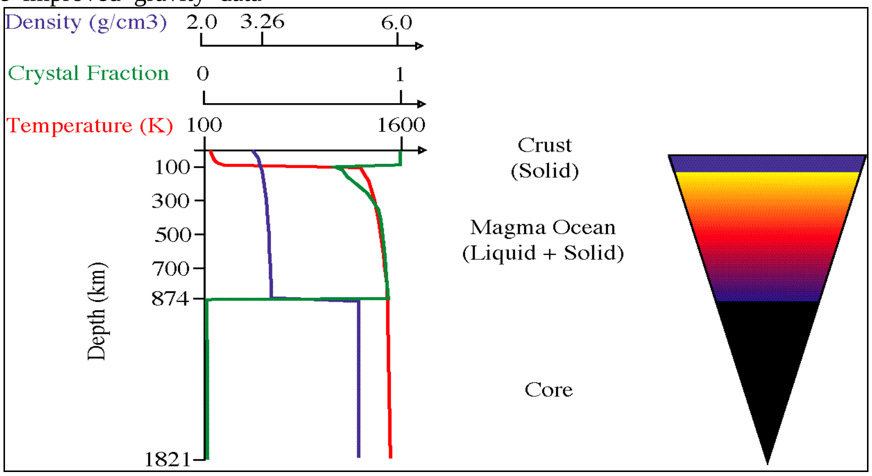

Figure 1. Predicted internal structure within a mushy magma ocean that reaches 1300 °C at the surface and attains a maximum of 40% partial melting. At 1500 °C the maximum degree of partial melting reaches 60% and the base of the magma ocean is 30% melt.